Calculation of SEL for Govoni et al. (2003, 2007) and Popper et al. (2007) Studies

Report for Amendment to Project 15218, J&S Working Group

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Introduction

In a Memorandum to Deborah McKee (CALTRANS) and Paul Wagner (WADOT) dated July 23, 2007, Thomas Carlson, Mardi Hastings and Arthur Popper summarized their recommendations for revised interim criteria for pile driving based on review of all available literature and data during a meeting facilitated by Dave Buehler in Arlington, VA, on July 19-20, 2007. Table 1 of the July 23rd memorandum indicated that a cumulative SEL (sound exposure level in dB re 1 μPa^2-s) recommendation for non-auditory tissue damage for juvenile fish and an improved recommendation for auditory tissue damage in hearing generalists could be determined by analysis of acoustic data provided in a report from J. J. Govoni and acoustic data in digital format available for the Popper et al. (2007) low-frequency active sonar study. This report summarizes the results of these data analyses and recommended sound exposure levels that can be used to update the July 23rd recommendations for revised interim criteria.

Analysis of Waveform Data for Govoni et al. (2003, 2007)

J. J. Govoni provided a copy of the instrumentation report (Lynch and Revy 2001), which contained graphical waveforms of received sound pressure levels for each blast test reported in the Govoni et al. 2003 and 2007 studies. This report also contained companion plots of the impulse and energy flux density (i.e., energy per unit area), and tabular ocean climate data recorded at the time of the test. Figure 1 illustrates the graphical data provided in Lynch and Revy (2001).

Govoni et al. (2003, 2007) reported impulse and energy flux density calculated for only the first 75 microseconds of the received pressure wave. Because many of the pressure waveforms had significant variations past 75 microseconds, the cumulative energy flux density was graphically evaluated out to the end of the waveform (200 microseconds) for the current analysis. Then the ocean climate data were used to convert energy flux density to sound exposure (see for example, Hamernik and Hsueh 1991).

Govoni et al. (2003, 2007) considered correlation of (non-auditory) tissue damage effects with peak pressure, impulse and energy flux density. As in previous studies (e.g., Yelverton et al. 1975) they found best correlation with the energy indices, impulse and energy flux density. They chose to correlate data with impulse ($\int pdt$) rather than energy flux density ($\frac{1}{\rho c}\int p^2 dt$) primarily because more experimental error was introduced by squaring the pressure signal.

In addition to the primary blast wave, the fish in this study received additional energy from reflections that could not be accounted for in the calculations by Govoni et al. (2003, 2007) or in the current analysis because these data were not provided for each shot. Figure 2 is an example of the waveform of the total sound pressure incident on the fish during one shot event. Hence the impulse values tabulated by Govoni et al. (2003, 2007) and the sound exposure values and SEL tabulated here are conservative.

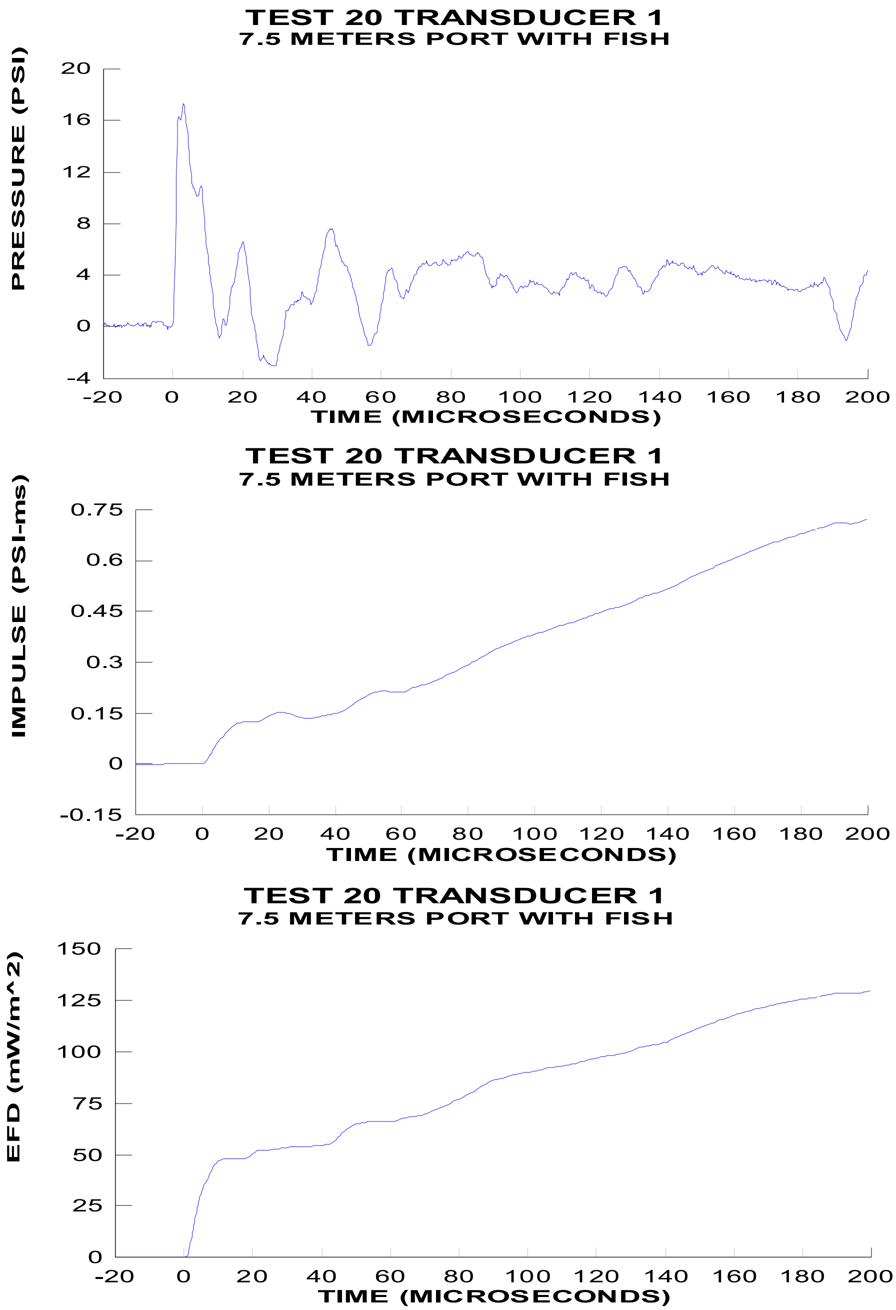

Figure 1: Example of graphical data provided for each shot in Lynch and Revy (2001). Note that units for energy flux density (EFD) are incorrect, but are correctly reported in by Govoni et al. (2003, 2007).

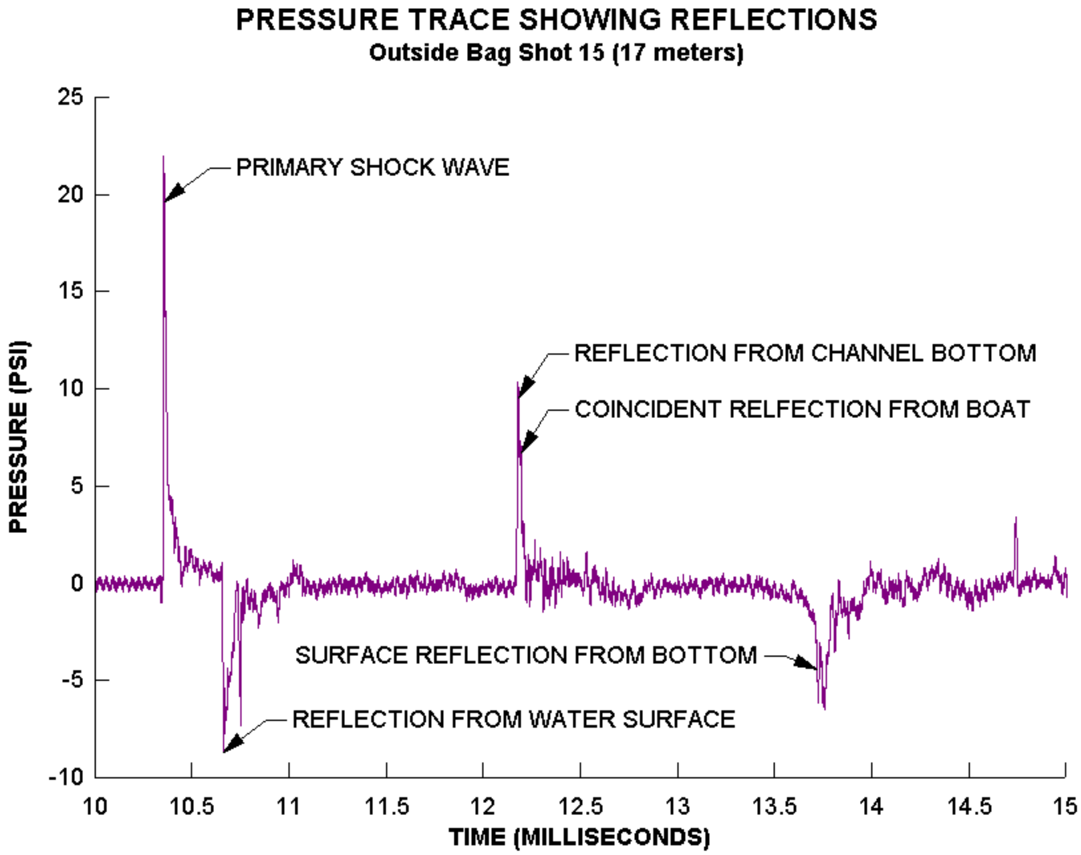

Figure 2: An example of the total pressure signal incident on juvenile fish in study reported by Govoni et al. (2003, 2007). Only the first 75 *microseconds* of the primary pressure waveform was used by Govoni et al. (From Lynch and Revy (2001), Figure 16, p. 14.)

Govoni et al. (2003, 2007) used a total of 232 (175 exposed, 57 control) spot (*Leiostomus xanthurus*) and 251 (190 exposed, 61 control) pinfish (*Lagodon rhomboides*) juveniles with mean standard lengths approximately 18-20 mm for spot and 16-17 mm for pinfish. Based on length-weight relationships available at www.fishbase.org for larger spot (50-125 mm total length) and pinfish (130-230 mm fork length), the estimated average masses are 0.06-0.08 g for spot and 0.12-0.14 g for pinfish used by Govoni et al. In addition they reported that spot were more susceptible to trauma than pinfish, which would be expected based on these estimates of mass. Figure 3 compares the average impulse data for each trial from Govoni et al. with results from Yelverton et al. (1975).

Table 1 summarizes the results of the current SEL analysis.

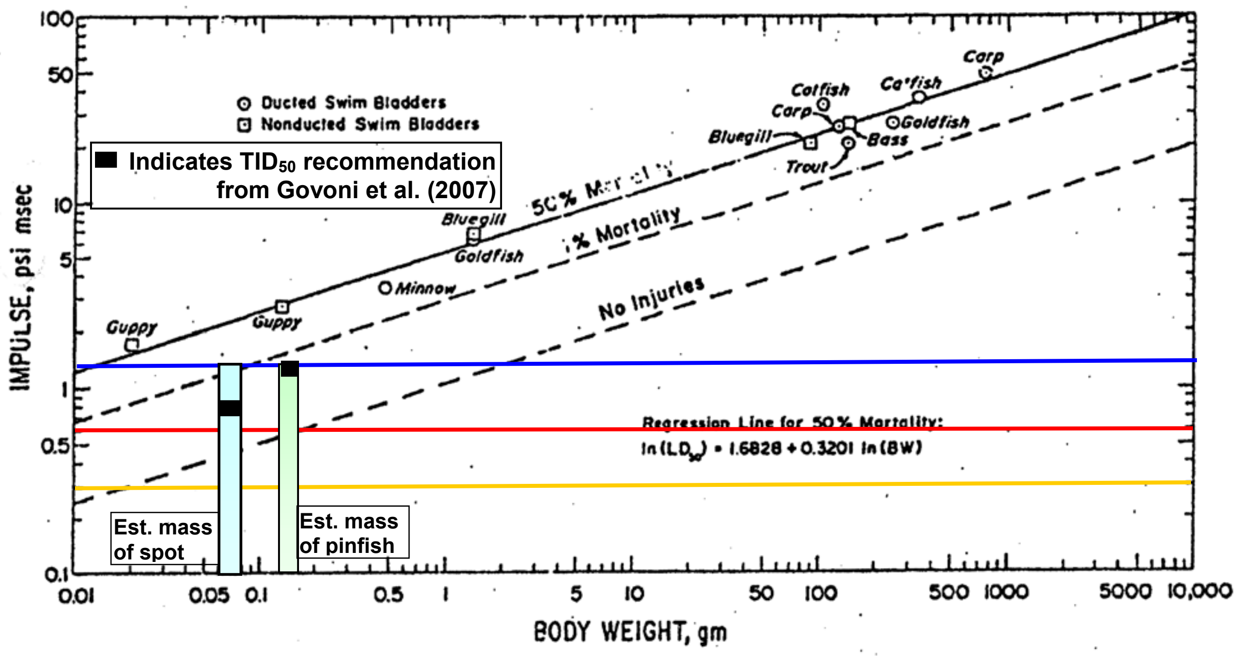

Figure 3: Average impulse values from Govoni et al. (2003, 2007) compared with results of Yelverton et al. (1975, Fig. 6). Distance from the explosive source is indicated by the color of the line: blue – 3.6 m; red – 7.5 m; and yellow – 17 m. Table 1 summarizes SEL's at these ranges.

Table 1: Summary of sound exposure data for Govoni et al. (2003, 2007) calculated from waveforms provided in Lynch and Revy (2001). The colored borders indicate distance from the source: blue – 3.6 m; red – 7.5 m; and yellow – 17 m (corresponds to line colors in Figure 3).

Shot #	Species	Energy Flux, J/m^2 (to 200 microseconds)	Water Density kg/m^3	Sound Speed m/s	Sound Exposure Pa^2-s	SEL dB re 1 μPa^2-s
16	Pinfish	1.44	1023.3	1493.5	2200750	183
16	Spot	3.91	1023.3	1493.5	5975647	188
17	Pinfish	2.67	1022.9	1493.0	4077596	186
17	Spot	2.53	1022.9	1493.0	3863790	186
18	Pinfish	3.07	1022.4	1492.6	4684925	187
18	Spot	1.22	1022.4	1492.6	1861762	183
19	Pinfish	0.600	1020.1	1489.5	911663	180
19	Spot	0.256	1020.1	1489.5	388976	176
20	Pinfish	0.131	1019.9	1489.6	199021	173
20	Spot	0.275	1019.9	1489.6	417792	176
21	Pinfish	0.633	1022.7	1494.6	967558	180
21	Spot	0.528	1022.7	1494.6	807062	179
22	Pinfish	0.129	1022.2	1494.1	197018	173
22	Spot	0.113	1022.2	1494.1	172581	172
23	Pinfish	0.129	1022.7	1494.1	197114	173
23	Spot	0.065	1022.7	1494.1	99321	170
24	Pinfish	0.108	1023.2	1495.0	165206	172
24	Spot	0.116	1023.2	1495.0	177443	172

In the Govoni et al. experiment each species was held in a plastic bag, one on either side of a boat, so two received levels were recorded for each shot. Their experiment had three trials (source located 3.6 m, 7.5 m, and 17 m range) consisting of three shots each. A proportion of all fish were injured when located 3.6 m from the source. Thus the lowest SEL of 183 dB re 1 μPa^2-s is recommended as an interim sound exposure criterion for non-auditory tissue damage in small juvenile and larval fish. This value is in agreement with the results of a dose-response regression analysis by Govoni et al. (2007) that assumed all injuries – including sublethal hematuria as reported in Govoni et al. 2003 – were lethal. These results estimated 50% Total Injury Dose (TID_{50}) at an impulse of 8.910 Pa-s or energy flux density of 1.168 J/m^2 for spot, and an impulse of 5.286 Pa-s or energy flux density of 1.483 J/m^2 for pinfish (indicated by ■ in Figure 3). Converting these energy flux densities to SEL using the average of ocean climate parameters given in Table 1, results in TID_{50} SEL's of 183 dB (re 1 μPa^2-s) for spot and 184 dB for pinfish.

NOTE: The Govoni et al. (2007) manuscript is still unpublished, so this reference is not available for distribution. Therefore it should not be referenced when updating the July 23, 2007, memorandum. Instead perhaps a reference to the personal communications between M. Hastings and J. J. Govoni could be used.

Analysis of Waveform Data for Popper et al. (2007)

G. M. Sisson, Marine Acoustics Inc., provided digital voltage waveform data from ten different low-frequency active sonar fish exposure experiments conducted at Senaca Lake in 2004, 2005, and 2006. These data included recordings from 6 hydrophones located inside the tank holding the fish and 1 hydrophone located just outside the tank. Hydrophone sensitivity was -203 dB (re 1 V/μPa). Trial data from three different test dates that fell within the timeframe of experiments reported by Popper et al. (2007) were analyzed using MATLAB®. The experiments consisted of either three 108-s exposures separated by 9 minutes, or three 216-s exposures separated by 18 minutes. Moreover the 216-s exposures consisted of two 108-s signals played back-to-back. The waveform data examined were consistent over time and over the volume of the test tank. The signals consisted of sweeps and tones as reported by Popper et al. (2007). The frequency range of the signals from the trials analyzed in this report was 150 to 350 Hz. Moreover a quick look at the waveforms indicated instantaneous peak sound pressure level could exceed 197 dB re 1 μPa.

The sound exposure for each 108-s signal was calculated by squaring the voltage waveform and integrating it in the time domain, and then converting it to SEL in dB by applying the hydrophone sensitivity. Figure 4 shows a typical plot of cumulative SEL for the signal received on hydrophone 3 during the first transmission on May 20, 2004. Table 2 summarizes the SEL values calculated for all three 108-s transmissions on all the hydrophones on three different test dates. The average received SEL for these transmissions is 210 dB re 1 μPa^2-s and the standard deviation is less than 1 dB. The 216-s transmission consisted of two 108-s signals (i.e., 2 'strikes'), so the average SEL for the 216-s experiments is just 3 dB higher, 213 dB re 1 μPa^2-s.

These results are in good agreement with SELs of 204 and 203 dB re 1 μPa^2-s reported by Finneran et al. (2007) for 64-s long tones with average SPLs of 186 and 185 dB re 1 μPa, respectively. SELs at these levels produced threshold shifts of 40-45 dB in a bottlenose dolphin that took four days to recover. Popper et al. (2007) reported threshold shifts of 20-21 dB in rainbow trout for SELs determined in the current analysis (210 and 213 dB re 1 μPa^2-s) that did not recover 24 and48 hours after exposure.

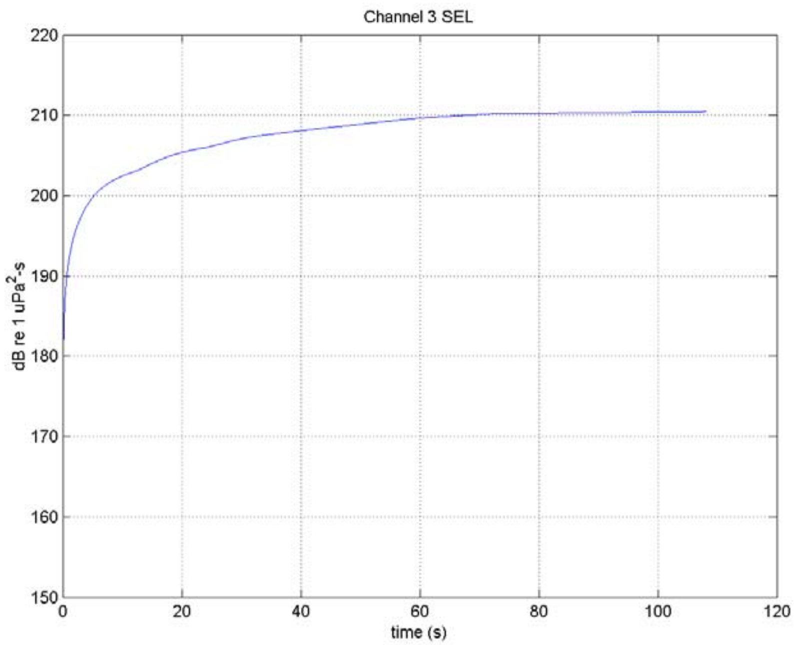

Figure 4: Cumulative SEL received at hydrophone 3 located inside the test tank during transmission of a 108-s low-frequency active sonar signal from Test 2A on May 20, 2004.

Table 2: Summary of calculated SELs (dB re: 1 μPa^2-s) received at seven different hydrophone locations for three 108-s transmissions on three randomly selected test dates for the fish exposure study by Popper et al. (2007). The overall average SEL is 210 dB.

	CHAN 1	CHAN 2	CHAN 3	CHAN 4	CHAN 5	CHAN 6	CHAN 7
20-May-04							
Test 2 A	208.4632	210.0548	210.4526	210.3900	210.3573	210.3458	210.0837
Test 2 B	208.5297	209.9711	210.4618	210.4679	210.3936	210.2679	210.0859
Test 2 C	208.5426	209.9386	210.4160	210.4152	210.3333	210.2157	210.0615
6-Jun-04							
Test 10 A	208.6456	209.9497	210.2409	210.7652	210.3143	209.9801	210.2981
Test 10 B	208.5899	209.9248	210.1932	210.6726	210.3498	210.0029	210.1944
Test 10 C	208.5518	209.8873	210.1663	210.5788	210.3671	209.9511	210.1308
8-Jun-05							
Test 43 A	207.7456	208.0215	209.3532	209.7354	209.7512	209.2087	209.4412
Test 43 B	207.7782	207.9306	209.2536	209.6074	209.6501	209.1440	209.3602
Test 43 C	207.8241	207.9616	209.3187	209.6231	209.6808	209.1738	209.4116

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